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# LARGE EXPERIMENTAL WIND TURBINES - WHERE WE ARE NOW

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# Large Experimental Wind Turbines - Where We Are Now

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Several large wind turbine projects have been initiated by NASA-Lewis as part of the ERDA wind energy program. The projects consist of progressively large wind turbines ranging from 100 kW with a rotor diameter of 125 feet to 1500 kW with rotor diameters of 200 to 300 feet. Also included is supporting research and technology for large wind turbines and for lowering the costs and increasing the reliability of the major wind turbine components. The results and status of the above projects are briefly discussed in this report. In addition, a brief summary and status of the plans for selecting the utility sites for the experimental wind turbines is also discussed.

## Introduction

Wind energy systems have been used for centuries as a source of energy for many applications. These applications have included sailing ships for transportation and windmills for providing mechanical energy. The windmill applications have included the pumping of water, the sawing of wood, the grinding of grain, and more recently the generation of electricity.

The recent national concern over the future availability of energy sources has resulted in the federal government's initiating a program to investigate alternative energy sources. The recently formed Energy Research and Development Administration (ERDA) has been assigned the responsibility for the management of there programs. Among the many alternatives under consideration is the utilization of wind energy. A recently published summary report of the Federal Wind Energy Program (Ref. 1) describes the scope of the federal wind energy program. This federal wind energy program includes several projects for the development of large horizontal-axis propeller-type wind turbines for generating electricity. Under the overall program management of ERDA, the NASA-Lewis Research Center (LeRC) will provide project management for the large horizontal-axis wind turbines projects and the associated supporting research and technology. This report briefly describes the status and results of these several wind energy projects and the plans under way for selecting the utility sites for these first large experimental wind turbines.

## Large Experimental Wind Turbines

The large wind turbine phase of the federal wind energy program has several projects, these include:

(1) The 125-foot-diameter rotor 100-kW wind turbine which has been designated Mod-0; this wind turbine became operational on September 4, 1976.

(2) Two 125-diameter-rotor wind turbines of 125 and 200 kW each.

These wind turbines are similar to the Mod-0 and have been designated Mod-OA. These two wind turbines are to become operational in selected utility sites in January and June of 1976.

(3) One or two nominal 200-feet-diameter rotor wind turbines of 1500 kW each. These wind turbines have been designated Mod-1 and are to become operational in selected utility sites in December, 1977, and June, 1978.

(4) A nominal 300-foot-diameter rotor wind turbine with an output of 1000 to 2000 kW. This wind turbine has been designated Mod-2 and is being designed to deliver 1000 kW or more at lower wind speeds than the above wind turbines. This Mod-2 wind turbine is to be operational by the end of 1979.

The planned schedule for these several projects is shown in Fig. 1.

100 kW Mod-0 Experimental Wind Turbine

The 100 kW experimental wind turbine project has been described in several earlier reports (Refs. 2 to 5). The objective of this project is to provide engineering data, as early as possible, for use as a base for the entire wind energy program and to serve as a test bed for improved components and subsystems. To meet this objective a 100 kW wind turbine was designed using current technology and catalog items where possible. Information in previously designed large two-bladed wind turbines was obtained from Hutter (Refs. 6 to 8) and Putnam (Ref. 9). The design, fabrication, and assembly of the 100 kW Mod-0 wind turbine was completed in approximately 18 months with initial operation beginning on September 4, 1976.

Description. The 100 kW wind turbine (Fig. 2) has a two-bladed 125-foot-diameter rotor driving a 100 kW synchronous alternator through a step-up gear box. The rotor is located downwind of the tower and rotates at a constant speed of 40 rpm. The alternator operates at 1800 rpm and delivers 60 Hz three-phase power. Details of the drive train assembly and yaw system are shown in Fig. 3. The wind turbine rotor starts rotating at a wind speed of 5 mph and reaches 40 rpm and begins to deliver power at 9.5 mph. Fig. 4 shows the variation of power output of the wind turbine as a function of wind velocity.

Assembly. The 100 kW wind turbine drive train was assembled at LeRC and tested prior to final assembly at the site. The drive train assembly was tested for 50 hours to make certain all components and subsystems worked satisfactorily (Fig. 5). The drive train assembly was then mounted in the yaw drive system and the rotor hub and blades attached (Fig. 6). In this condition all systems were checked except for rotation of the blades. The blades were then removed and the system was transported to the site for final checkout and assembly.

Final site assembly. The wind turbine was assembled on a test stand near the base of the tower (Fig. 7(a)). After all systems were checked out, the wind turbine was lifted on the morning of September 4, 1976, and assembled and placed on the tower by a crane (Figs. 7(b) and (c)). This operation took approximately 4 hours and went very smoothly.

Test results. Checkout of the wind turbine systems and preliminary operation, performance, and engineering data were obtained over the next several months. Fig. 8 is a plot of predicted blade angle at 40 rpm versus wind speed to obtain 0 kW or 100 kW. Shown in the figure are several test points at 0 kW and 100 kW for different wind speeds; these test points agree fairly well with the predicted values. On December 18, 1976, the wind turbine was operated for the first time at the design conditions of 40 rpm and 100 kW. When electric power is generated by the wind turbine, the wind turbine is connected to a variable resistance load bank. To date, the wind turbine is performing as expected except for larger than expected bending movements at the blade

roots. During testing at wind speeds of 27 mph these bending moments are nearly twice as high as expected. Fig. 9 shows the predicted and actual blade bending moment during one revolution of the blade. Zero degrees is with the blade straight down behind the tower. The expected bending moment was calculated from the MOSTAB helicopter rotor loads computer code modified for wind turbines (Ref. 10). Assuming the tower retarded the wind by 24 percent, the MOSTAB code predicted a cyclic bending moment that varied from -60 000 ft-lb to about 4 000 ft-lb. The actual test data, however, showed the bending moment varying from -120 000 ft-lb to 7 000 ft-lb. The MOSTAB code nearly predicts this larger bending moment if it is assumed the tower retards the wind by 93 percent behind the tower. Analysis and tests are underway to fully understand this problem and to determine ways to reduce the blade bending moments.

Test plans. In addition to understanding the larger than expected blade bending moments planned wind turbine tests include the following:

(1) Full mapping of all operational conditions including failure modes to determine blade, tower and mechanical loads, and wind turbine performance.

(2) Automatic startup and shutdown including synchronization to the local utility network.

(3) Measurement of effects of rotor in downstream winds to determine how close together wind turbines can be spaced.

(4) Monitoring of local television receivers to determine if the wind turbine blades have any effect on reception.

(5) Measurement of tower deflections and rotor noise.

(6) Connecting the wind turbine to a small (100 to 200 kW) diesel electric generator to simulate operation of the wind turbine when connected to a small power system.

Also, the Mod-0 will be used as a test bed for evaluating components developed under the supporting research and technology project such as composite blades and teetered hubs. A teetered hub is a rotor hub that allows the rotor blades to move a few degrees in and out of the plane of rotation to reduce the blade root bending moments.

125 to 200 kW Mod-OA Experimental Wind Turbine Project

The objective of the Mod-OA project is to gain early experience with wind turbines operating in utility networks. In particular we plan to obtain actual utility interface requirements, operations information, and uncover any institutional problems for wind turbines operating in conjunction with a utility network.

To meet this objective, two wind turbines similar to the 100 kW Mod-0 wind turbine but of higher power output are in the process of being fabricated. Both wind turbines have been slightly re-designed to increase their power output from 100 kW at 18 mph to 200 kW at 23 mph. However, the first Mod-OA wind turbine will be initially rated at 125 kW since it utilizes a spare gearbox from the Mod-0 wind turbine to provide a faster schedule. We plan to later replace this 125 kW gearbox with a 200 kW gearbox. Both Mod-OA wind turbines will use 200 kW alternators. The rotor blades for the Mod-OA will be identical to the metal blades in use on the Mod-0 wind turbine.

The Mod-OA towers will be of the steel truss design similar to the Mod-0. The Mod-OA towers, however, are being designed to minimize blockage of the wind and to therefore reduce the effect of tower shadow in the blade bending moment. The Mod-OA towers will utilize a simple cable supported electric personnel lift for access to the top with a simple ladder for use in the event of an emergency in place of the Mod-0 tower staircase.

Both studies show that at each medium wind speed the energy costs are higher at the lower power levers over the range studied. The GE study shows that energy costs continue to go down very slowly with increased power level for all medium wind speeds. The Kaman studies show, however, a bottoming effect to the curves with energy costs increasing as power levels go above approximately: (1) 700 kW at 12 mph, (2) 800 kW at 15 mph; and (3) 1500 kW at 18 mph. The fact that one curve has a minimum while the other continues to slowly decrease is primarily due to the difference in assumptions used for the rotor costs as the diameter goes up.

The energy costs for the parametric studies shown in Fig. 14 differs by up to a factor of two. These were early studies and are based on the conceptual design results. Later in the program as the preliminary design studies at 1500 kW and 500 kW were completed, the cost differences between the two studies come closer together with the Kaman energy costs decreasing and the GE costs increasing. The cost estimates resulting from the preliminary designs are shown as data points (+) for each of the designs in Fig. 14. These later energy costs were calculated using the estimated capital costs, energy capture and the yearly rate of charge for money, operation, maintenance, taxes, etc. The GE study uses a rate of approximately 0.16/year while Kaman used approximately 0.20/year. This difference also accounts for a major difference between the energy cost results of the earlier parametric studies shown by the solid lines in Fig. 14. To compare the energy costs from both studies, the 0.16/year rate was used to calculate energy costs for each wind turbine preliminary design and these energy costs are shown as data points (+) on Fig. 14. The following equation was used for calculating energy cost:

$$\frac{¢}{\text{kW-hr}} = \frac{(\text{Total capital cost}) \times (0.16/\text{yr})}{(\text{kW-hr})/\text{yr}}$$

Referring to Fig. 14 it can be seen that the energy cost estimates for the Kaman 500 kW and 1500 kW design are 5.5 ¢/kW-hr and 2.0 ¢/kW-hr, respectively, while the energy cost estimate for the GE 500 kW and 1500 kW designs are 4.2 ¢/kW-hr and 1.7 ¢/kW-hr, respectively.

In addition to minimum energy cost there is also the question of the wind turbine plant factor. Plant factor (PF) is defined as the ratio of the energy the wind turbine will deliver over a year for mean wind speed to the amount of energy it would generate in a year if it operated at rated power continuously.

$$PF = \frac{\text{Generated annual-kW hr}}{\text{Rated kW} \times 8760 \text{ hr}}$$

Plant factor gives an indication of how effectively a wind turbine is being utilized. High plant factor wind turbines generally have large rotors in comparison to their rated power output or alternator size and thereby operate more hours at rated output. However, wind turbines with high plant factors will not necessarily generate the lowest cost energy. High PF wind turbines generally capture more energy but are also more expensive to build because of the larger rotors.

The selection of a minimum energy cost wind turbine versus a wind turbine with a higher PF is definitely an issue that depends on how the wind turbine is to be used. If the application can use bulk energy whenever it is available, then the minimum energy cost design is preferred. If energy storage is needed, then the higher plant factor wind turbine probably will result in the best overall systems choice. This option is clearly dependent on the resultant user's application.

Before selecting the wind turbine sizes and the mean wind speeds for preliminary design, the following question was addressed: How sensitive to mean wind speed is an optimized design? That is, given an optimized design of, say, 1500 kW for an 18 mph site, what is the effect on energy costs of putting this design on sites with a mean wind speed of 15 mph or 21 mph. Studies were conducted by both contractors to answer this question. The results of these studies for a 500 kW wind

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turbine, 12 mph mean wind speed site and a 1500 kW wind turbine, 18 mph mean wind speed site are plotted in Fig. 15.

Significantly, the results show that for less than 10 percent increase in energy costs the wind turbine designed for 500 kW at 12 mph can be used at sites with 9 to 15 mph and the 1500 kW design can be used at sites with 15 to 21 mph wind. Thus it appears that the two designs could be used for a relatively wide range of sites with only a small penalty in energy cost.

From the results of the parametric study and optimization tasks, two designs were selected for further definition during the preliminary design task; 500 kW at 12 mph and 1500 kW at 18 mph. The conceptual, and parametric analysis studies were performed to obtain the minimum energy cost wind turbine designs. However, in the final selection attention was paid to plant factor and the designs selected were slightly off optimum to take advantage of higher plant factors at increase in energy cost of only a few percent. The capital cost of these higher plant factor wind turbines is greater but because more energy is generated, the resulting energy costs are nearly those of the minimum energy-cost design.

Table I summarizes the results of the 500 kW and 1500 kW wind turbine designs for each of the contractors. Figs. 16 and 17 show the artist concepts for the GE and Kaman wind turbine designs.

In addition to determining the optimum wind turbine designs, a major task of the design studies was to determine the interface requirements for connecting wind turbines to typical utility grids. These interface requirements included items such as required electrical interface switchgear, automatic protection and controls and required operation and maintenance procedures. Fig. 18 summarizes the interface requirements. Fig. 17 identifies some of the operational and institutional issues considered. These studies show no interface or institutional problems that pose major barriers to the installation of wind turbines on utility grids.

This paper does not summarize all the results of the four design study tasks but has only discussed the major results. The two final contractor reports will contain all the information determined from the two parallel design studies.

Fabrication, assembly, and initial operation contact. A competitive request for proposals (RFP) is planned to be issued in the spring of 1976 for the detail design, fabrication, assembly, and initial operation of a 1500 kW wind turbine. The specifications for this wind turbine were determined from the design study contacts with some specifications left as optional. We plan to have this contractural effort under way during the summer of 1976 and to have the 1500 kW wind turbine assembled and ready for initial operation by December, 1977. A decision to build a second wind turbine will depend on proposed costs and funding available. The utility sites for these two wind turbines will be selected according to the plan described later in this paper.

1000 to 2000 kW Mod-2 Experimental Wind Turbine Project

The object of the Mod-2 project is to develop large wind turbines that can generate low-cost electricity when operating at sites that have median wind speeds near 12 mph. Preliminary designs of these wind turbines indicate that rotors of approximately 300 feet in diameter are required for optimized wind turbines at the 12 mph median wind sites. The present federal wind energy plan calls for the operation of the first of these large wind turbines to occur near the end of 1979. At the present time the plans and procurement packages for the design, fabrication, assembly, and initial operation of such a wind turbines are being prepared.

## Supporting Research and Technology

In parallel with the large wind turbine projects, a supporting re-

search and technology project (SR&T) has been implemented. The objective of this project is to reduce the costs of wind turbine components and subsystems, simplify the overall designs, and to make the wind turbines more reliable.

Rotor Systems

Low-cost rotor blades. The major emphasis of the SR&T project is directed toward reducing the costs of the rotor systems. The Mod-0 and Mod-1 projects have clearly shown that the rotor systems offer the greatest potential for reducing costs. Several tasks have been initiated to explore low-cost technologies for manufacturing rotor blades, these include: (1) the design and fabrication of filament wound composite blades for the Mod-0 wind turbine; (2) the investigation of prestressed materials such as concrete and the use of variable density urethanes; (3) low-cost methods of fabricating all metal blades similar to the present Mod-0 blades.

Large rotor blades. Another major effort of the SR&T project is directed toward the fabrication of large blades, nominally 150 feet, for the future large Mod-2 wind turbines. A major task will be initiated in 1976 for the analysis, design, fabrication, and ground testing of a nominal 150 foot rotor blade.

Rotor hubs and blade pitch controls. The SR&T project also contains tasks for the investigation of low-cost, reliable hubs. These tasks include the analysis, design, fabrication, and testing of selected hubs in the Mod-0 wind turbine. One hub under consideration is a teetered hub that allows the two blades to move in an art-of-the-plane of rotation. Such a system is expected to reduce the blade bending moments and result in lower-cost and/or longer life blades. The advantages of a teetered hub have been reported by Spera (Ref. 10). A three-bladed hub is also under consideration as well as other hubs and methods of blade attachment for possible tests on the Mod-0 wind turbine. The purpose of the three-bladed tests would be to experimentally quantify the difference in loads between two-bladed and three-bladed wind turbines. Such test results may be important as the wind turbine program is directed toward progressively larger wind turbines to take advantage of the many available lower wind speed sites.

Towers

The Mod-0 100 kW wind turbine has a steel truss tower similar to many of the utility transmission towers. The Mod-1 design studies investigated steel shell and concrete towers in addition to the steel truss towers. The design studies showed that the steel shell and concrete towers could compete with the truss tower economically if they were produced in sufficient quantity and if favorable soil conditions existed. These alternate towers appear to most persons to be more esthetically pleasing than the truss towers and will be investigated as well as other designs that show promise in futher detail under the SR&T project.

Other Components

In addition to the rotor systems and the towers, other major wind turbine components and subsystems will also be investigated under the SR&T project. These include the gear boxes, the alternators, the electric control systems, and the yaw systems for orienting the rotor into the wind. As particular components and subsystems show promise for simpler and/or lower cost wind turbines, they will be tested in the field on the Mod-0 wind turbine. The Mod-0 wind turbine is designed to serve the wind energy program as a test bed for obtaining the necessary engineering and operation data for evaluation of promising components and subsystems.

## Utility Site Selection

In parallel with the design and fabrication projects a plan has

been developed for selecting sites for the Mod-OA and Mod-1 wind turbines.

Background. To initiate the site selection action inquiries were sent in 1974 to many of the utility companies in the United States. These inquiries briefly described the wind energy program and asked the utility companies if they were interested in participating in the program. A meeting was held at the LeRC in December, 1974, with approximately 40 representatives of 30 utility companies. At this meeting the wind energy program was described and a proposed plan presented for site selection and the degree of involvement of the utilities. Since the December, 1974, meeting, additional utilities have expressed interest in possible participation. In December, 1975, ERDA sent a second invitation, this time to all the utilities listed in the Electrical World Directory. To date, a total of 63 utilities have indicated an interest in possible participation in the Mod-OA and Mod-1 wind turbine experiments. Fig. 20 shows the locations of these utilities.

Site selection plan. A plan has been developed for selecting utility sites for the first experimental wind turbines. This plan in the form of a Request for Proposals (RFP) will be mailed out in the spring of 1976, to all the utility companies that have indicated an interest in possible participation in the program. The utility companies will have 6 weeks in which to return proposals describing their proposed wind turbine sites. The sites will be evaluated by an ERDA/NASA team with the final selections made by ERDA. ERDA plans to select a minimum of 12 sites. These sites will be selected primarily to maximize the amount of information for the wind energy program and for the whole utility industry. In addition, the following site factors and variables are considerations for the 12 site selection:

Wind energy available at the site

Utilities utilization of variable wind power

Mode of power generation, the wind turbine will interface with, hydro, steam, diesel, etc.

Size of utility company and network

Cost of competitive power

Geographical location and environment

Project visibility to assess public reaction

Site meteorological data. The government plans to install towers and instrumentation in each of the 12 sites selected to measure the site wind data. The towers will be 165 feet tall and will have annemometers and wind direction sensors at two altitudes. The towers, instrumentation, and recording equipment will be installed and serviced by a government contractor. The utility companies will be expected to install the meteorological tower foundations and to check the towers and recording equipment on a regular basis. The data from the towers will be recorded automatically, but it is to be collected by the utilities regularly and mailed to the government contractor. The contractor will be responsible for all reduction of meteorological data and for preparing summary reports for each of the sites. It is expected that the meteorological tower will be similar to the tower now being used at the 100 kW wind turbine site at Plum Brook (Fig. 21).

Mod-OA and Mod-1 wind turbine sites. The sites for the Mod-OA and Mod-1 wind turbines will be selected from the above 12 sites. These sites will be selected based on the results of the wind data and the other considerations listed above. The sites will be selected as needed to allow time for site preparation prior to final assembly of the wind turbines at the sites. The planned schedule for the site situations is shown in Fig. 22. When a wind turbine site is selected, the plan calls for both the government and the utility to provide some

items. The government is to supply at no cost to the utilities the following major items:

(1) The wind turbine and its foundation

(2) All necessary controls, instrumentation, and recording equipment

(3) NASA and NASA contractor personnel for installation, checkout, maintenance, and general support during the 2 years of operation.

The utilities will be asked to provide the following at no cost to the government:

(1) The site on which the wind turbine is to be located

(2) Site preparation including an access road, control room, security fencing, and necessary electrical interface equipment

(3) Personnel to interface with NASA and the NASA contractor during site preparation, final assembly and checkout, and personnel for operation and routine maintenance of the wind turbine for up to 2 years.

## Concluding Remarks

Several large wind turbine projects have been initiated by NASA-Lewis as part of the ERDA wind energy program. This paper has briefly discussed the results and status of these projects.

1. A 100 kW experimental wind turbine was assembled in September 4, 1975, at the NASA Plum Brook site Sandusky, Ohio. The wind turbine achieved rated power of 100 kW at 18 mph and 40 rpm in December 18, 1975. The wind turbine has been undergoing experimental testing to obtain engineering data over the full operation range. The wind turbine has been performing as expected except for some larger than expected blade bending moments. These blade bending moments appear to be the result of the wind retardation caused by tower blockage. Analysis and tests are underway to understand and reduce these bending moments. To date, the WT has been operated into a variable resistance load bank. Tests for operating the wind turbine connected to the local utility network are planned for early 1976. Additional tests are planned for determining wind velocity retardation through the tower, TV interference from rotor blades and tests to determine the effects of the rotor in the winds downstream of the rotor. This latter test is needed to determine how close together wind turbines can be placed without seriously reducing these power outputs.

2. Two wind turbines of similar design to the Mod-0 are under fabrication for operation in utility networks. The objective of these upgraded Mod-0 wind turbines (Mod-OA) is to obtain early operating experience with utilities. These two machines are scheduled for initial operation in January and June of 1977. The sites are to be selected in the summer and winter of 1976.

3. Preliminary design studies for the Mod-1 wind turbines have been completed. These studies concluded that a constant rpm two-bladed rotor located downwind of the tower with the drive train assembly and alternator located on the top of the tower provides the lowest cost wind turbine designs. The studies showed that an optimized 1500 kW wind turbine operating on a site with a median wind speed of 18 mph could generate electricity at 1.7 to 2.0 ¢/kW hr if these wind turbines were produced in quantities of 100 a year or greater. The studies also showed that a wind turbine optimized for an 18 mph site could be operated on a site with a median wind speed of 15 mph with an increase in energy cost of only 10 percent over that of a wind turbine optimized for the 15 mph site. A request for procurement has been advertized for the detail design, fabrication, assembly, and initial operation of one

or two nominal 200 foot diameter rotor 1500 kW wind turbines. These wind turbines are planned for installation in December, 1977, and June, 1978, on utility sites to be selected.

4. A program plan is presently being prepared for the design, fabrication, assembly, and installation of a nominal 300 foot diameter rotor Mod-2 1000 kW wind turbine. This wind turbine will be designed to produce low-cost electricity at the many lower wind speed sites available in the United States.

5. A supporting research and technology (SR&T) project has been initiated to develop the technology for large low-cost wind turbines. The major efforts of the SR&T project are directed toward the rotor system. The Mod-0 project and Mod-1 design studies showed that the rotor system is the highest cost subsystem of the wind turbine. Contracts for composite blades, and pre-stressed concrete, and urethane model blades have been initiated to investigate low-cost blade technology. Also, a task to design, fab, assemble, and test a large 150 foot blade (300 ft/rates) are underway. In addition, to rotor blades, tasks for reducing the costs of towers, drive train assemblies, and the major subsystems are underway.

6. Plans for selecting utility sites for large experimental wind turbines are well underway. An ERDA invitation for participation in the program was sent in December, 1975, to all the utilities in the U.S. listed in the Electrical World Directory. A request for proposals was sent by ERDA in March, 1976, soliciting proposed wind turbine sites from the 63 utilities that have expressed interest in participating in the program. Twelve or more candidate sites are to be selected in the early summer of 1976. These 12 sites will be supplied with government installed meteorological towers instrumentation and data recording equipment for determining the site wind data. The sites for the early experimental wind turbines will be selected from these sites.

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ENERGY TECHNOLOGY III

TABLE I. - RESULTS OF PRELIMINARY DESIGN TASK FOR 500 kW AND 1500 kW Mod-1 WIND TURBINES

| | 500 kW | | 1500 kW | |
|---|---|---|---|---|
| | GE | Kaman | GE | Kaman |
| Mean Wind Speed | 12 | 12 | 1[illegible] | 18 |
| Rated Power, kW | 500 | 500 | 1500 | 1500 |
| Rated Wind Speed, mph | 16.3 | 20.5 | 22.5 | 25 |
| Energy Capture, kW-hr/yr | $1.88 \times 10^6$ | $1.3 \times 10^6$ | $6.6 \times 10^6$ | $5.7 \times 10^6$ |
| Rotor Diameter, ft | 183 | 150 | 190 | 180 |
| Rotor Solidity, % | 3 | 3 | 3 | 3 |
| Rotor Speed, rpm | 29 | 32 3 | 40 | 34.4 |
| Energy Cost, ¢/kW Hr[a] | 4.2 | 5.5 | 1.7 | 2.0 |
| Capital Cost, $/kW | 974 | 901 | 449 | 481 |
| Wind Turbine Cost, $ | 486 000 | 450 670 | 674 000 | 720 800 |
| Plant Factor | 0.42 | 0.29 | 0.51 | 0.43 |

[a]Assumed 16 percent of capital costs per year for interest, operations, maintenance, taxes, etc.

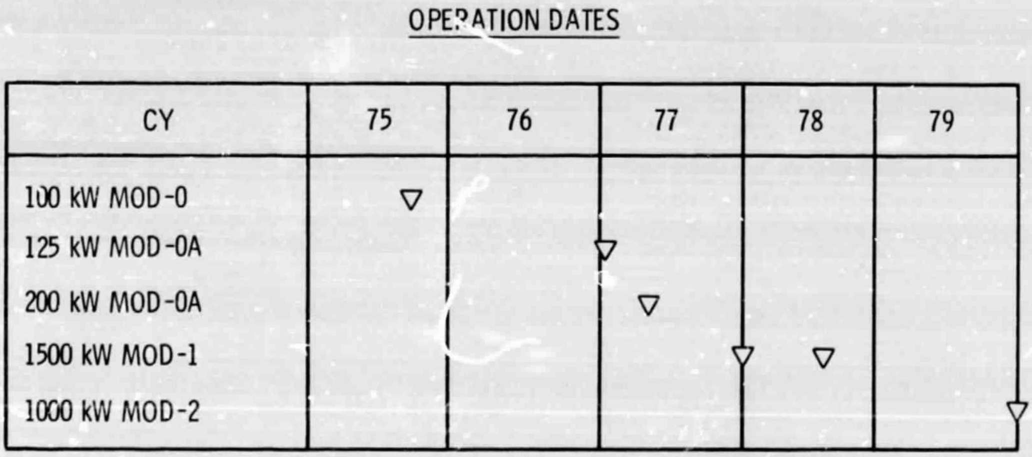



Figure 1. - Schedule - large experimental wind turbines.

CS-76112

E-8674

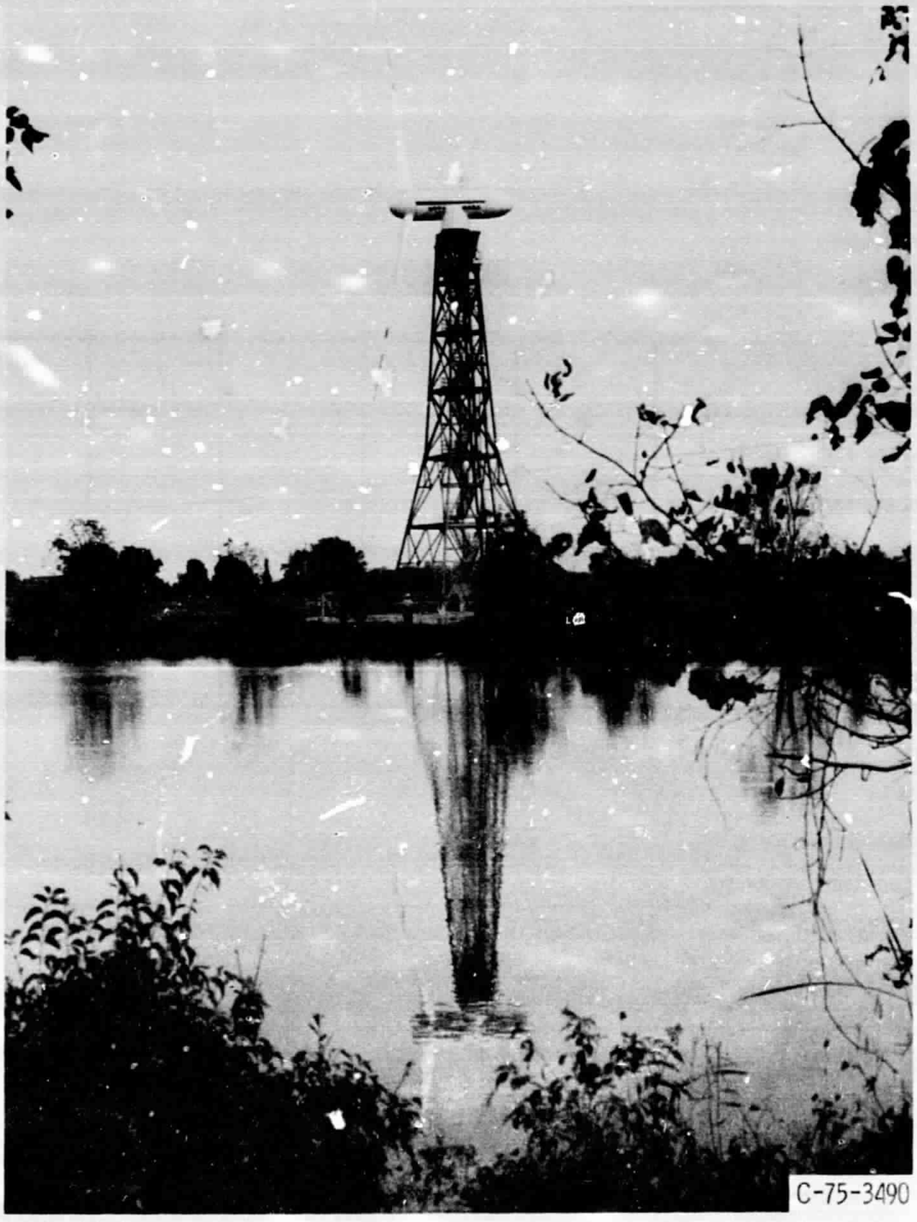
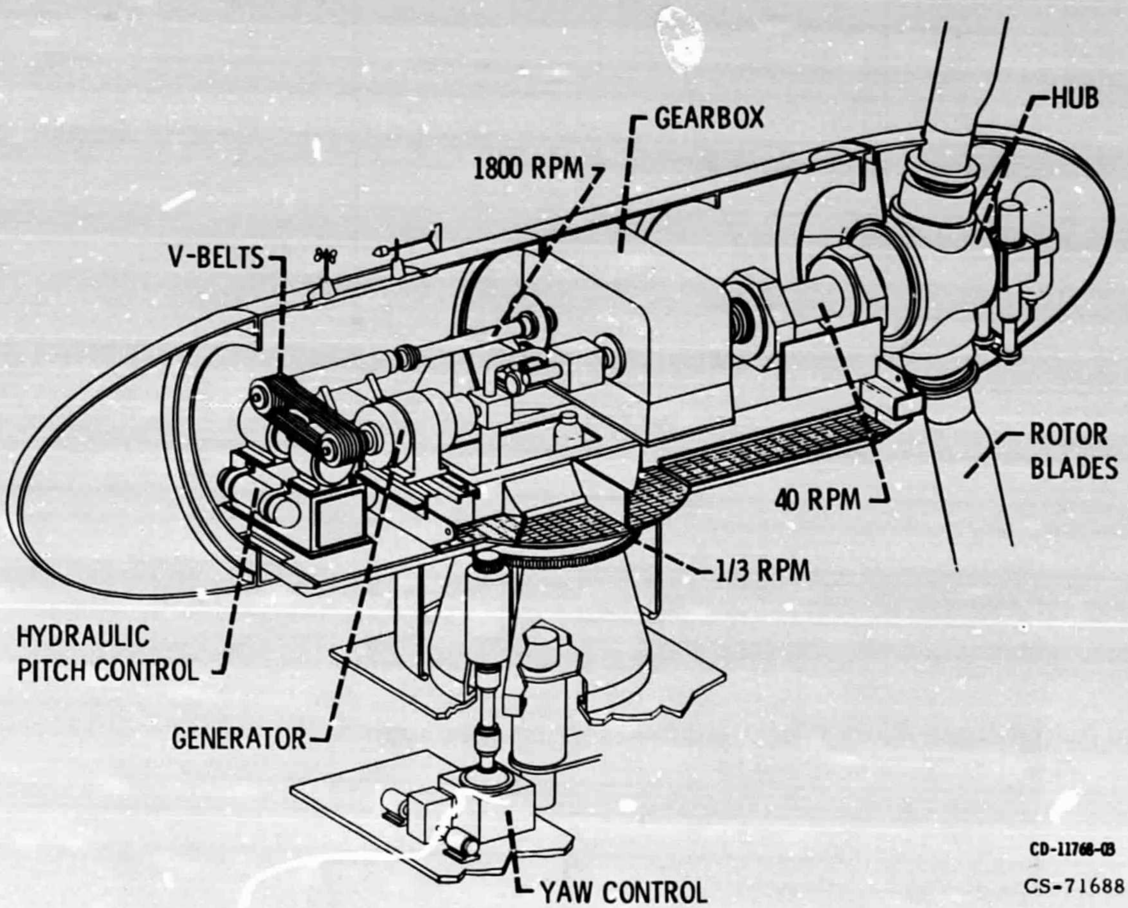



Figure 2. - ERDA/NASA 100 KW experimental wind turbine.

E-8674




CD-11768-03

CS-71688

Figure 3. - 100 kW wind turbine drive train assembly and yaw system.

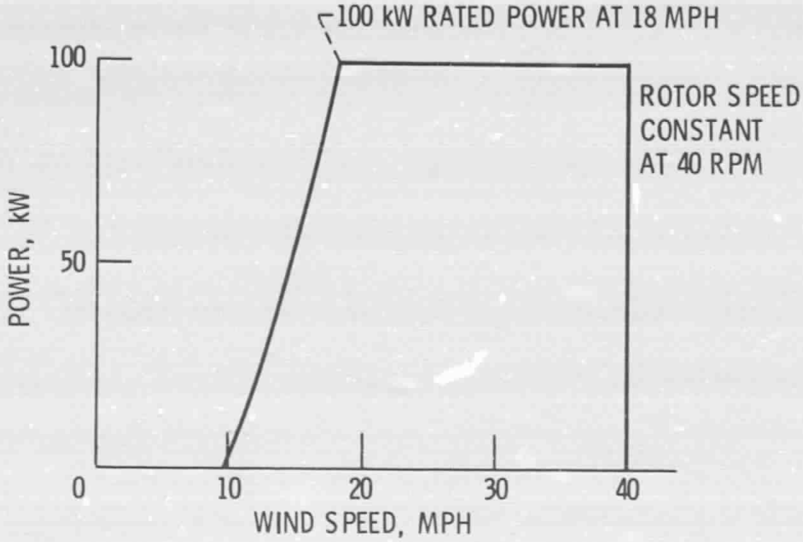



Figure 4. - Power out versus wind speed for the 100 kW wind turbine.

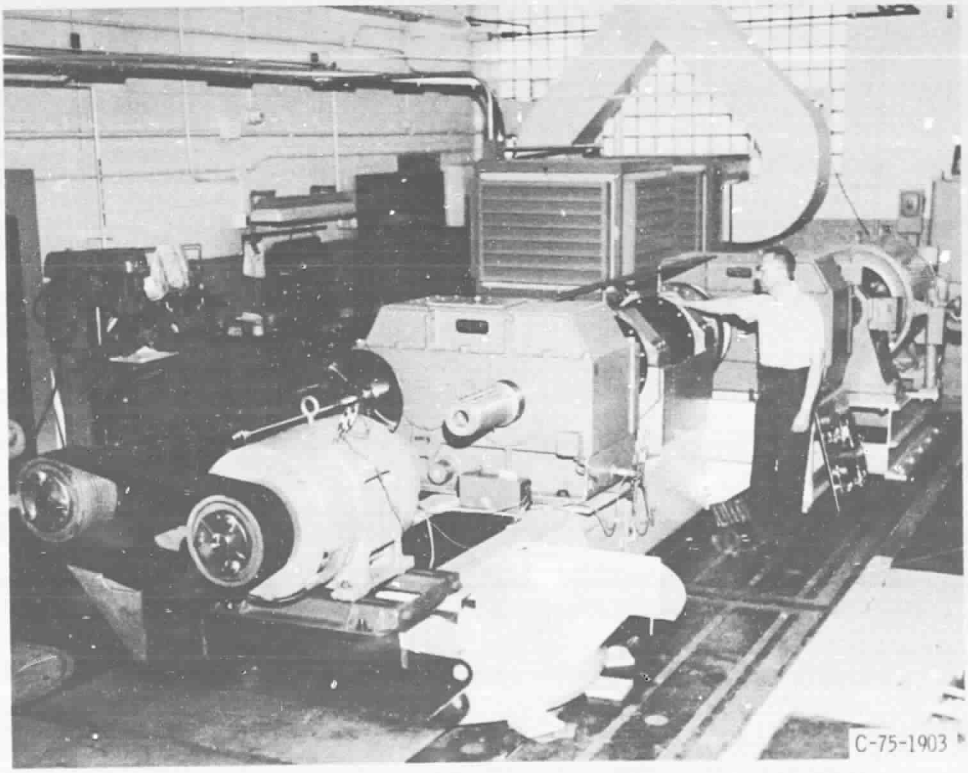



Figure 5. - 100 KW Wind turbine power train assembly under test.

E-8674

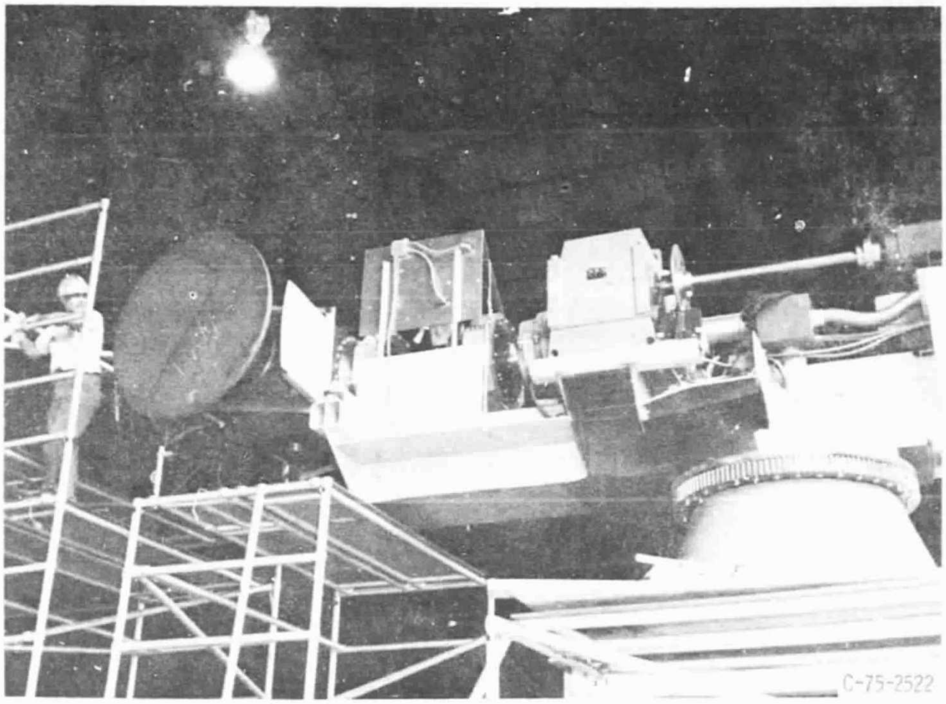



Figure 6. - Hub, drive train assembly and rpw system checkout for 100 KW wind turbine.

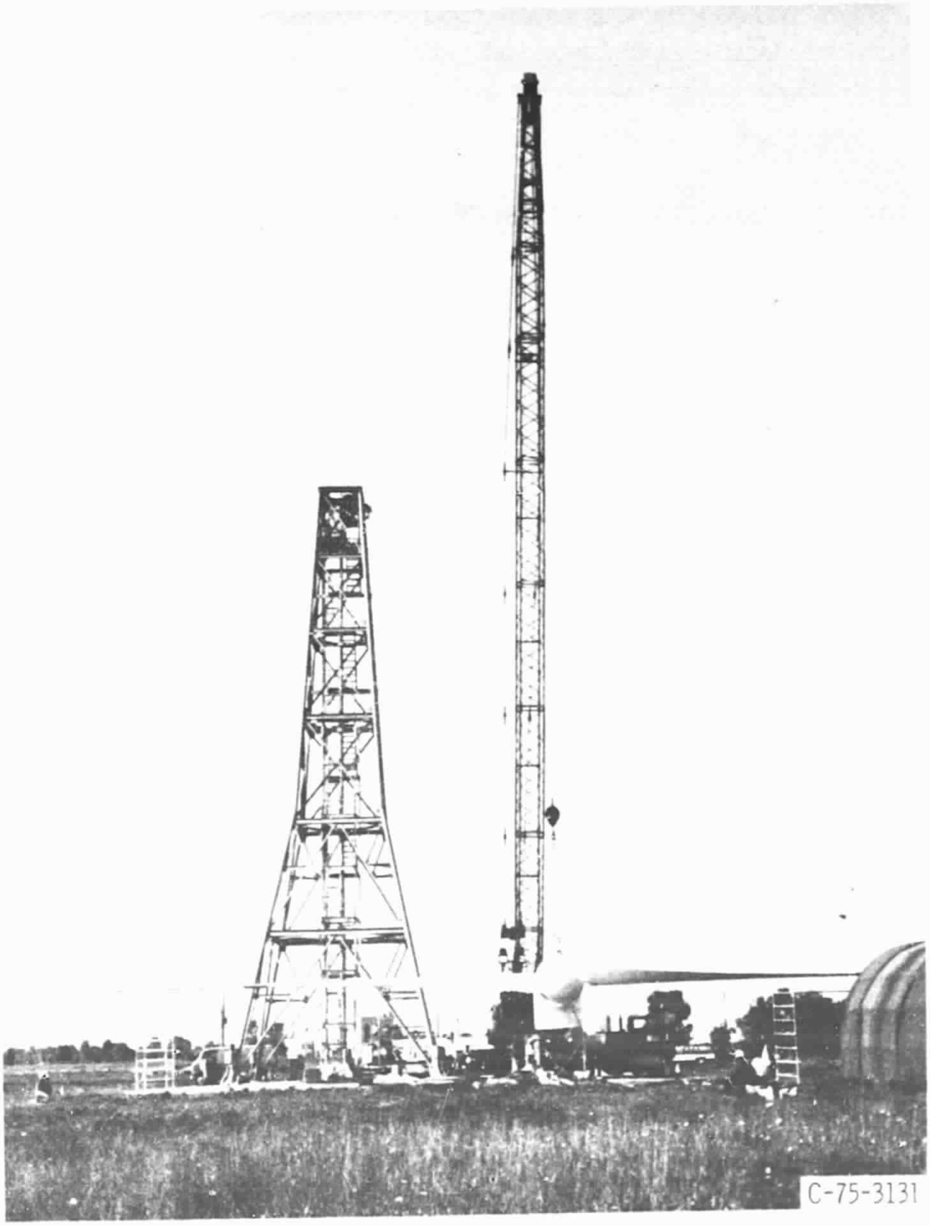



Figure 7(a). - 100 KW Wind turbine on test stand prior to installation.

E-8674

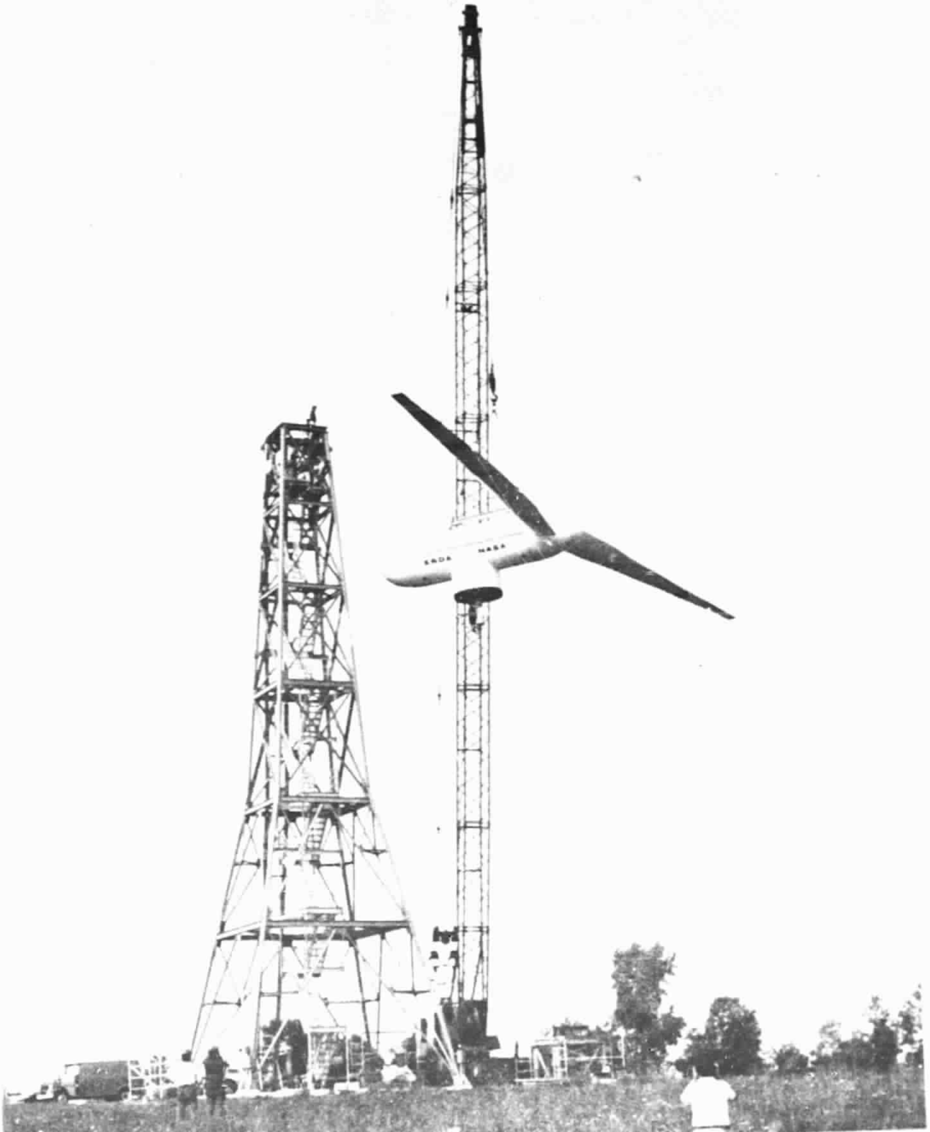



Figure 7(b). - 100 KW Wind turbine being lifted to top of tower.

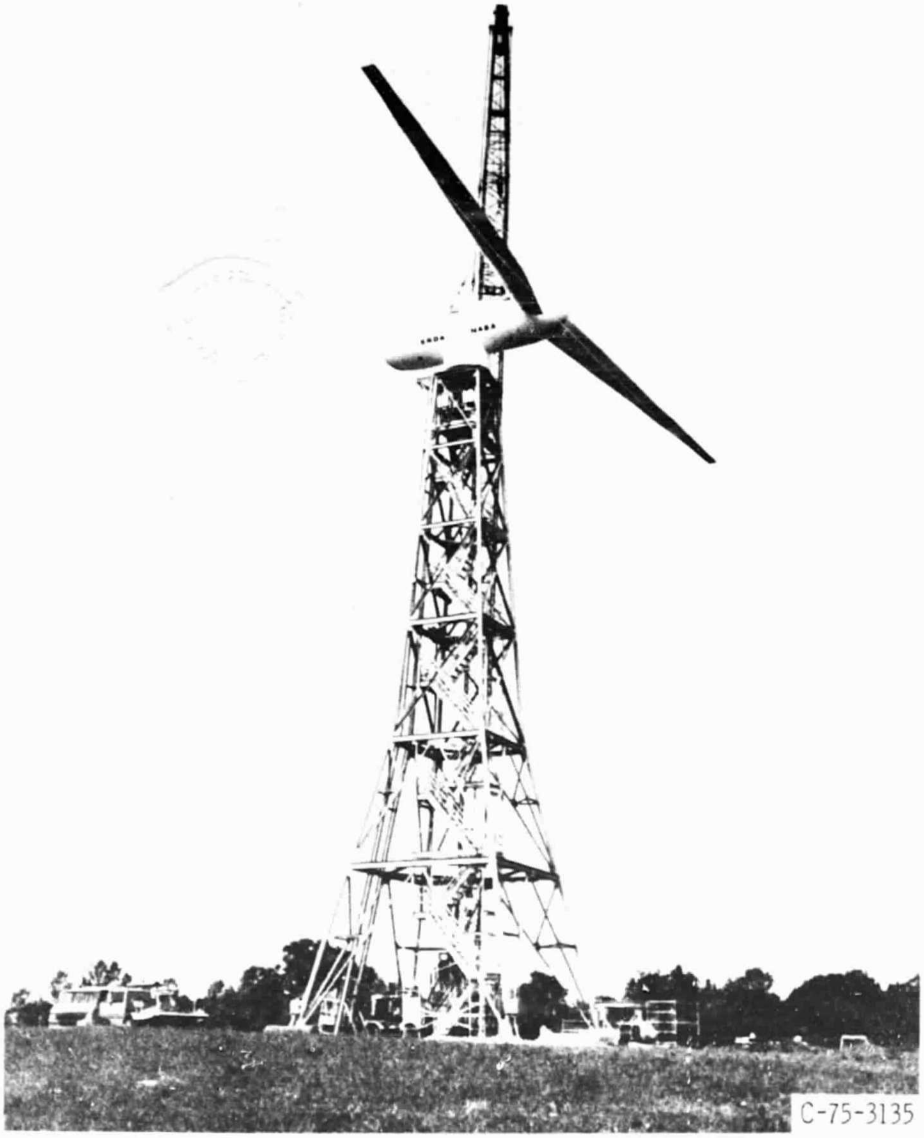
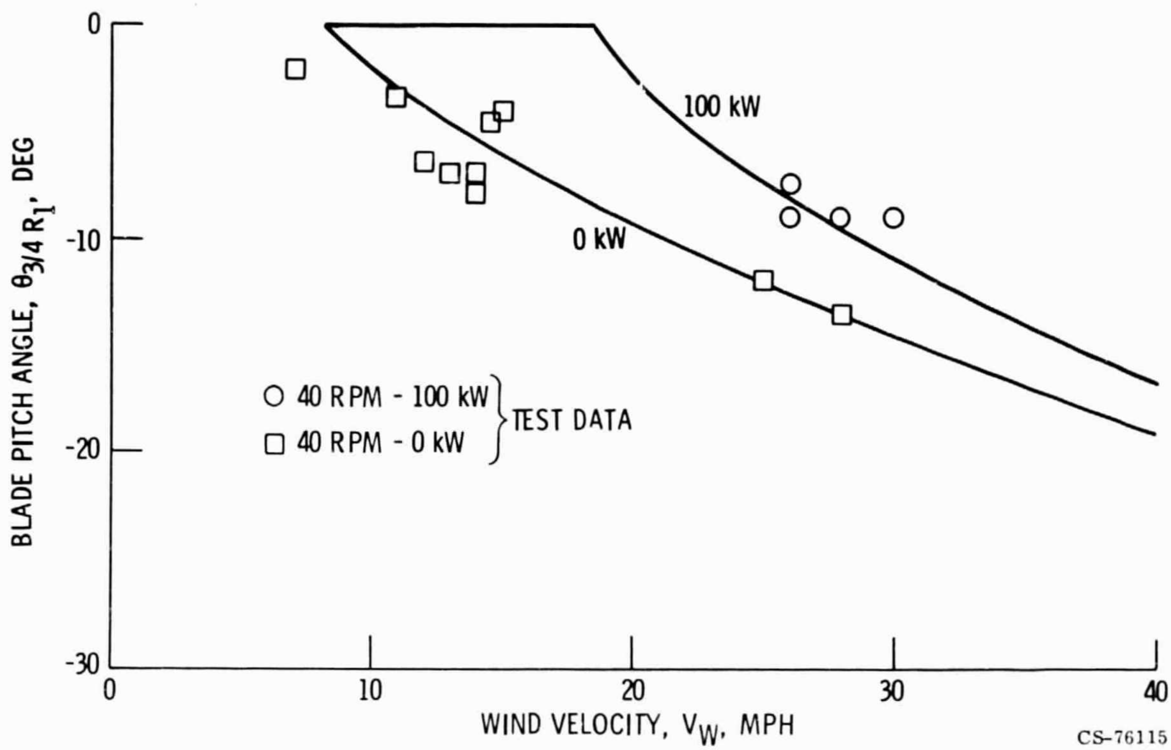



Figure 7(c). - 100 KW Wind turbine installed in top of tower.

E-8674




CS-76115

Figure 8. - Mod-0 blade pitch angle schedule.

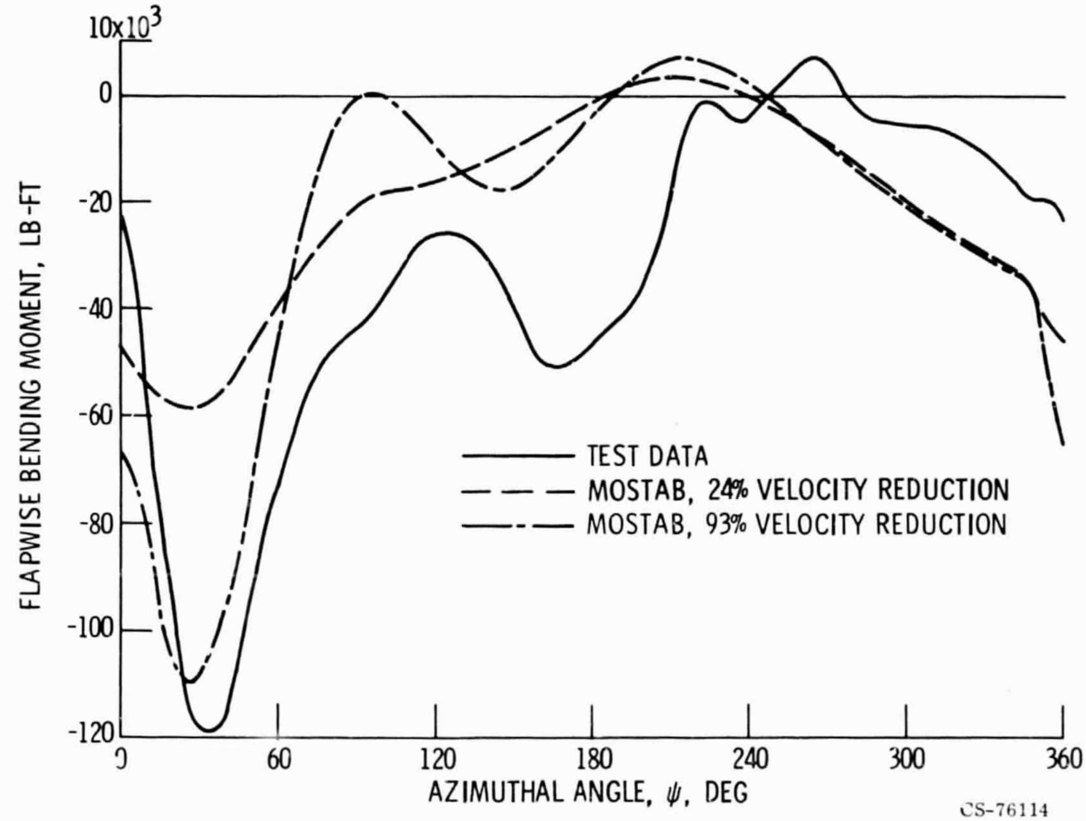



Figure 9. - Blade load comparison for MOSTAB predictions vs. test data. 40 rpm, 100 kW, $\theta_P = -8^0$, $V_{WIND} \cong 27$ mph.

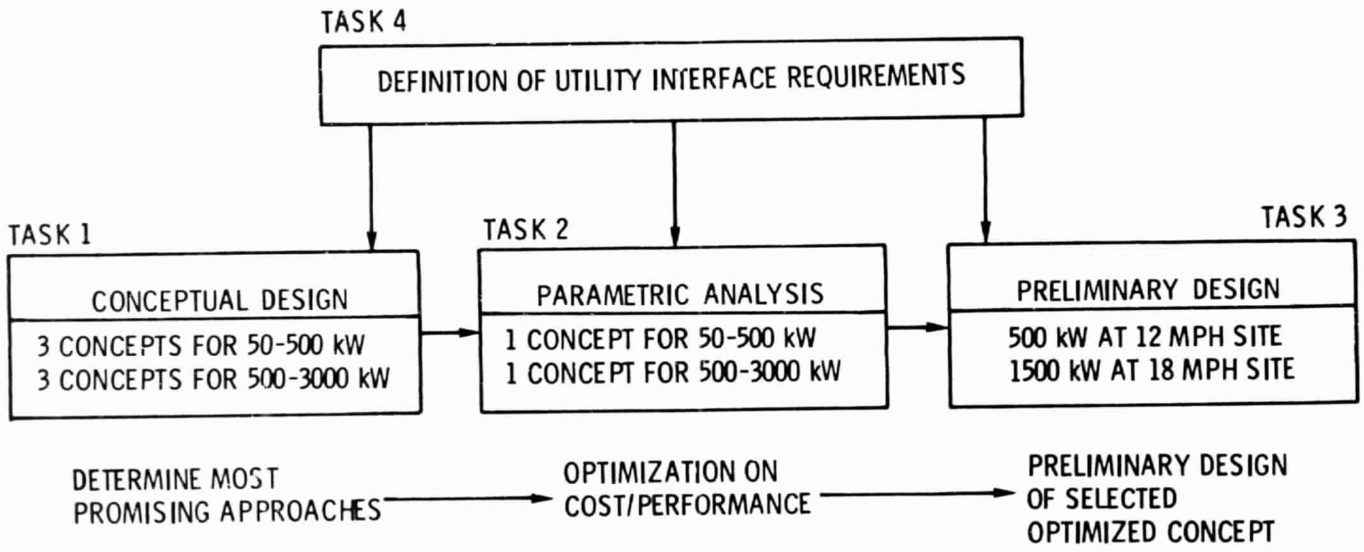



Figure 10. - Wind turbine design study tasks.

ROTOR

CONSTANT OR VARIABLE SPEED
DIAMETER
NUMBER OF BLADES
TWIST, TAPER, AIRFOIL
FIXED PITCH, VARIABLE PITCH
UPWIND OR DOWNWIND OF TOWER

TOWER

OPTIMUM HEIGHT
TYPE - TRUSS, GUYED POLE, SHELL, CONCRETE

MECHANICAL TRANSMISSION

GEAR BOX (FIXED OR VARIABLE RATIO)
CHAIN DRIVE, BELT AND PULLEYS

GENERATOR

SYNCHRONOUS, INDUCTION, DC

Figure 11. - Mod-1 wind turbine tradeoff considerations.

ROTOR

TWO BLADED
CONSTANT RPM (PITCH CONTROL)
RIGID HUB
TWIST, TAPER (STILL OPTION)
DOWNWIND OF TOWER

TOWER

TRUSS, SHELL, CONCRETE

MECHANICAL TRANSMISSION

GEAR BOX (FIXED RATIO)

GENERATOR

SYNCHRONOUS (INDUCTION IS AN OPTION)

LOCATE MAJOR EQUIPMENT ON TOP OF TOWER

Figure 12. - Mod-1 wind turbine study results.

E-8674

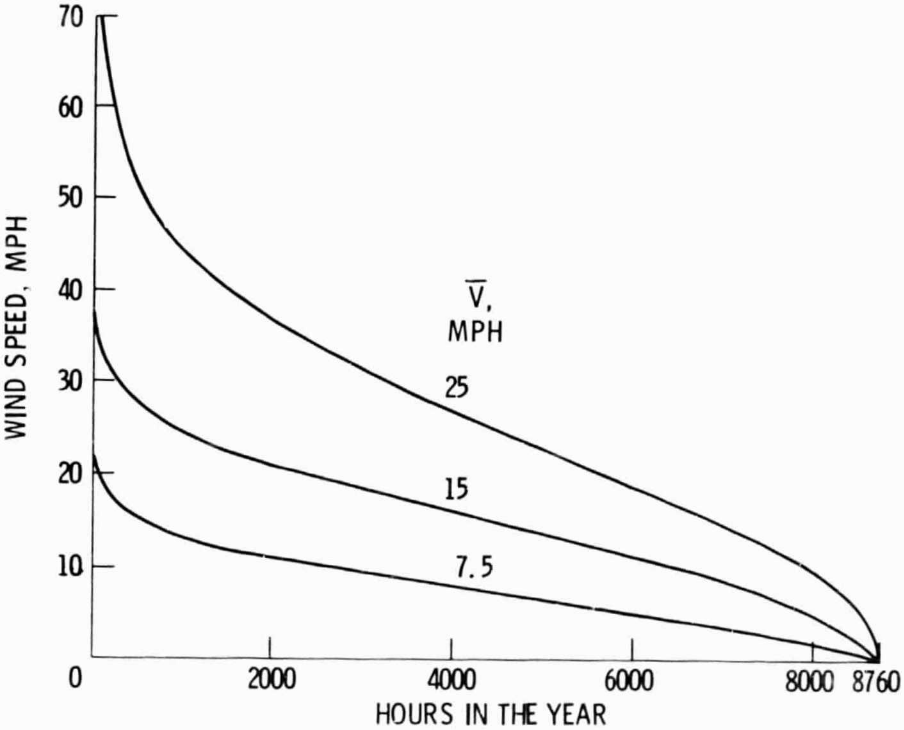



Figure 13. - NASA furnished wind velocity duration curves (30 ft elevation).

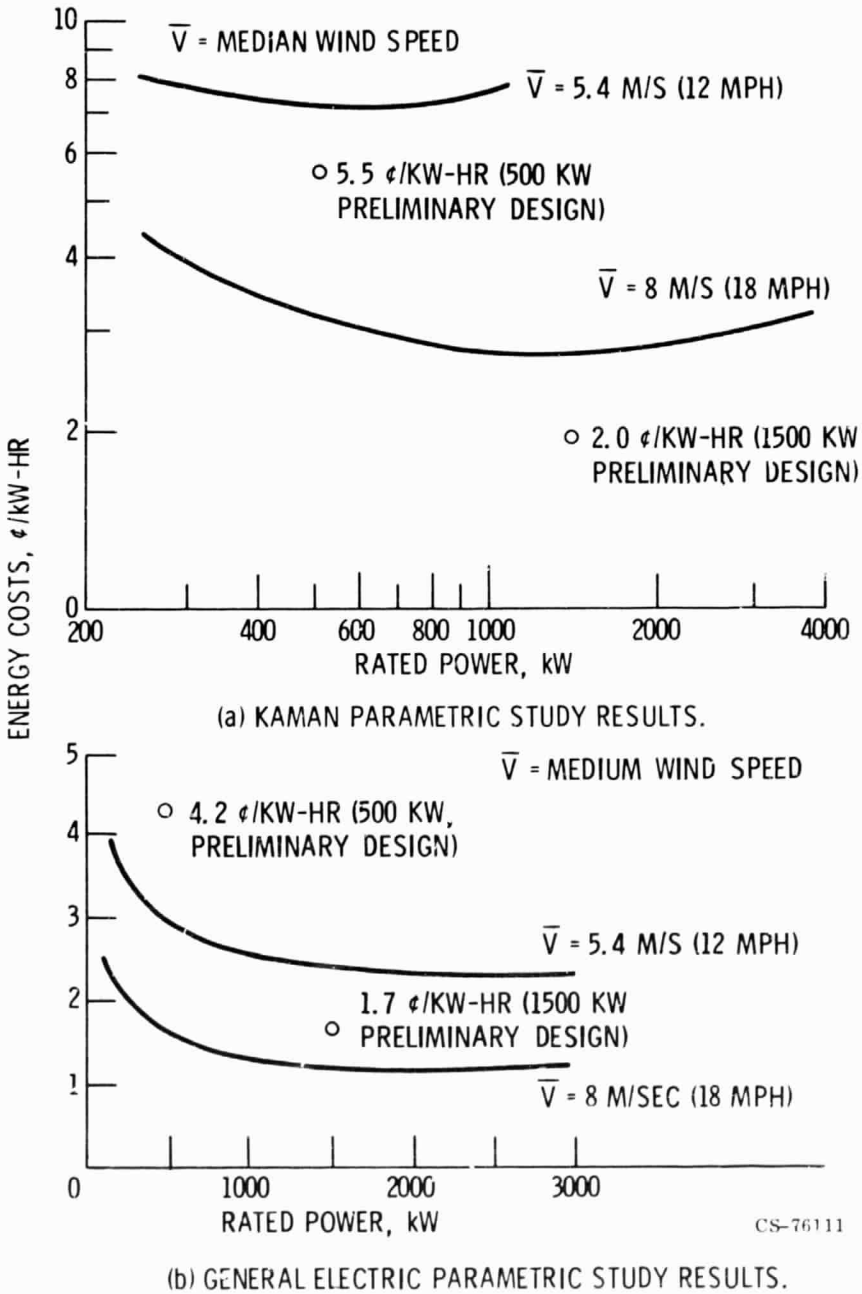



Figure 14. - Wind turbine energy costs as a function of median wind speed and rated power.

E-8674

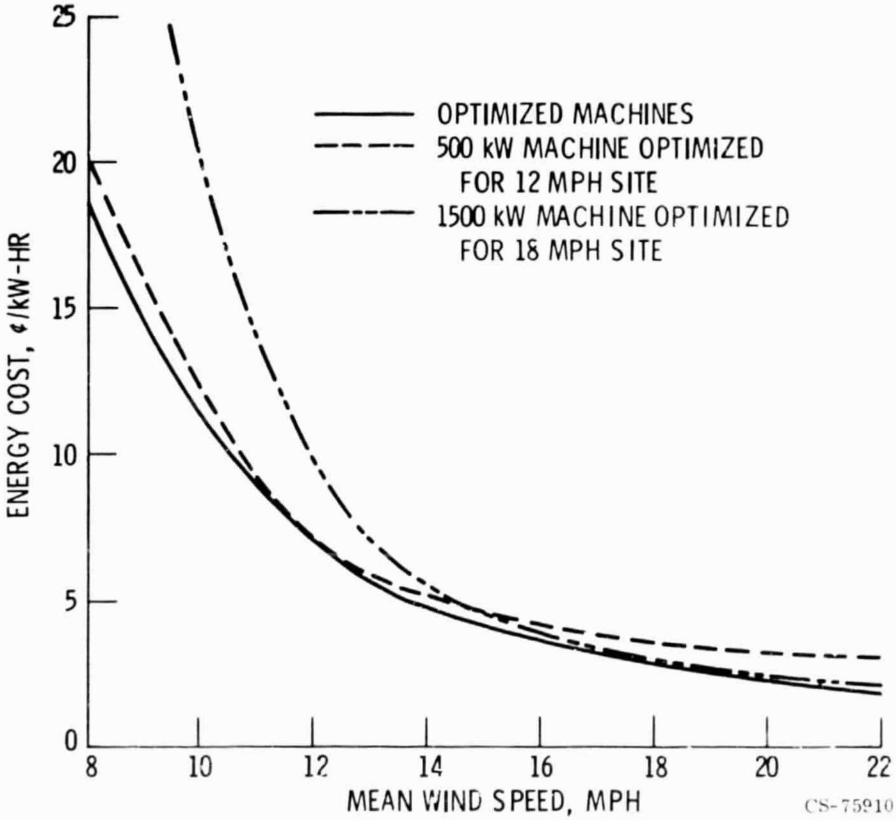



Figure 15. - Effect of siting-12 and 18 mph optimized machines located in various wind regimes.

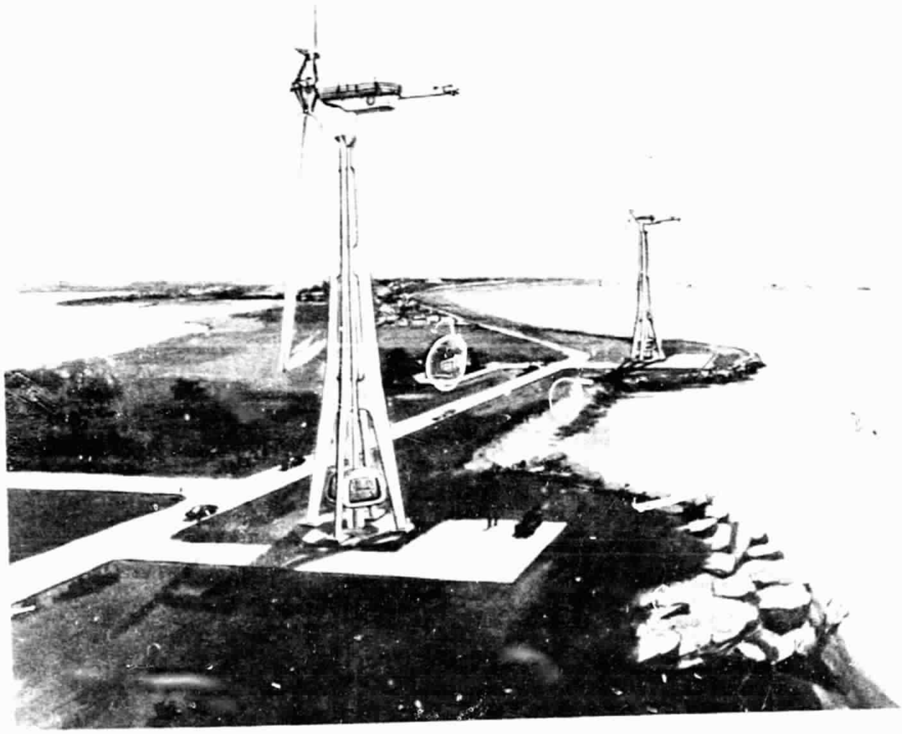


Figure 16. - GE 1500 KW wind turbine.

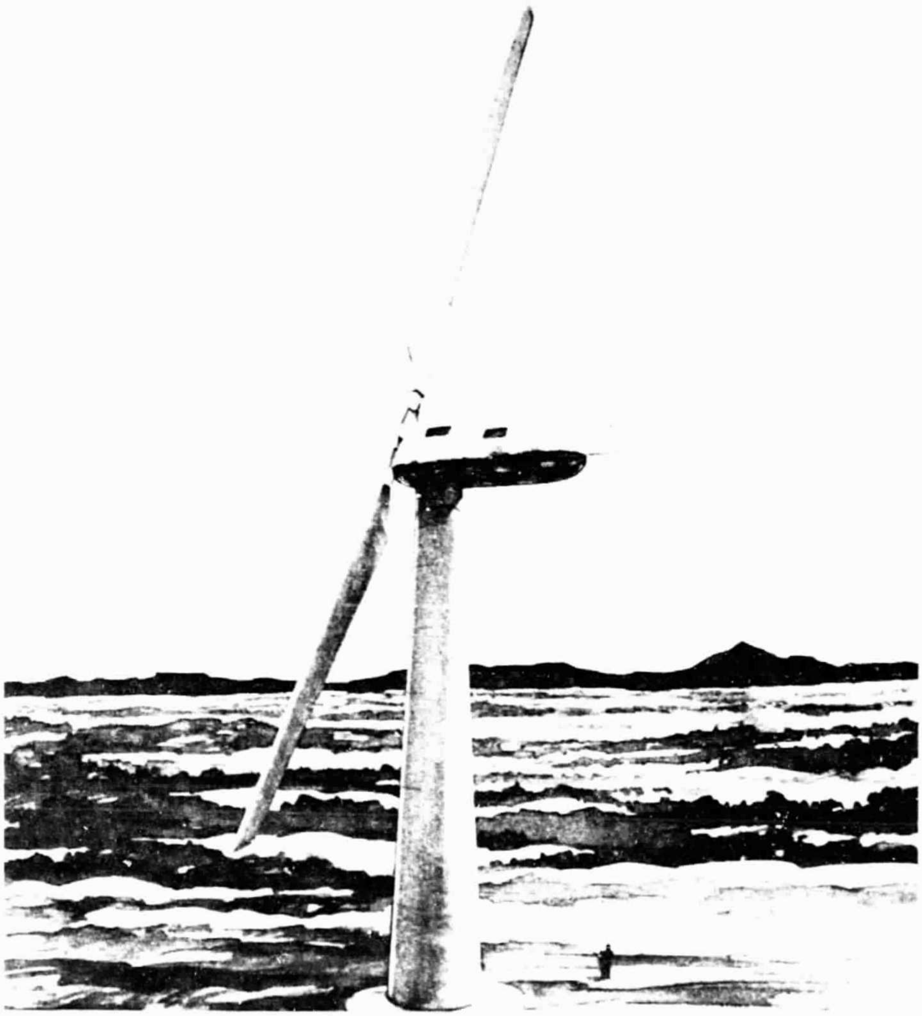


Figure 17. - Kaman 1500 KW wind turbine.

MANUAL DISCONNECTS MANDATORY
SINGLE BREAKER ON TRANSFORMER HIGH SIDE
UNIT CONNECTIONS TO DISTRIBUTION SYSTEM
LOCK OUT FOR INTERNAL FAULTS
RE-SYNC FOR EXTERNAL FAULTS - (STAND BY MODE)
  1 MINUTE DELAY - LOCK OUT AFTER 3 CYCLES
SEPARATE STATION SERVICE TRANSFORMER
EMERGENCY POWER - BATTERY 48 V
PF CAPACITORS - HIGH SIDE, SEPARATE BREAKER
REGULATION & STABILITY REQUIREMENTS DEPEND ON SITE
LIGHTNING SUPPRESSION AT GENERATOR & TRANSFORMER
DISTRIBUTION VOLTAGES FROM 2400 TO 34 500 V

Figure 18. - Wind turbine interface requirements for connection to a utility grid.

MAINTENANCE AND SAFETY
ENVIRONMENTAL IMPACT
LICENSING
APPLICATIONS

Figure 19. - Wind turbine operational and institutional issues.

E-8674

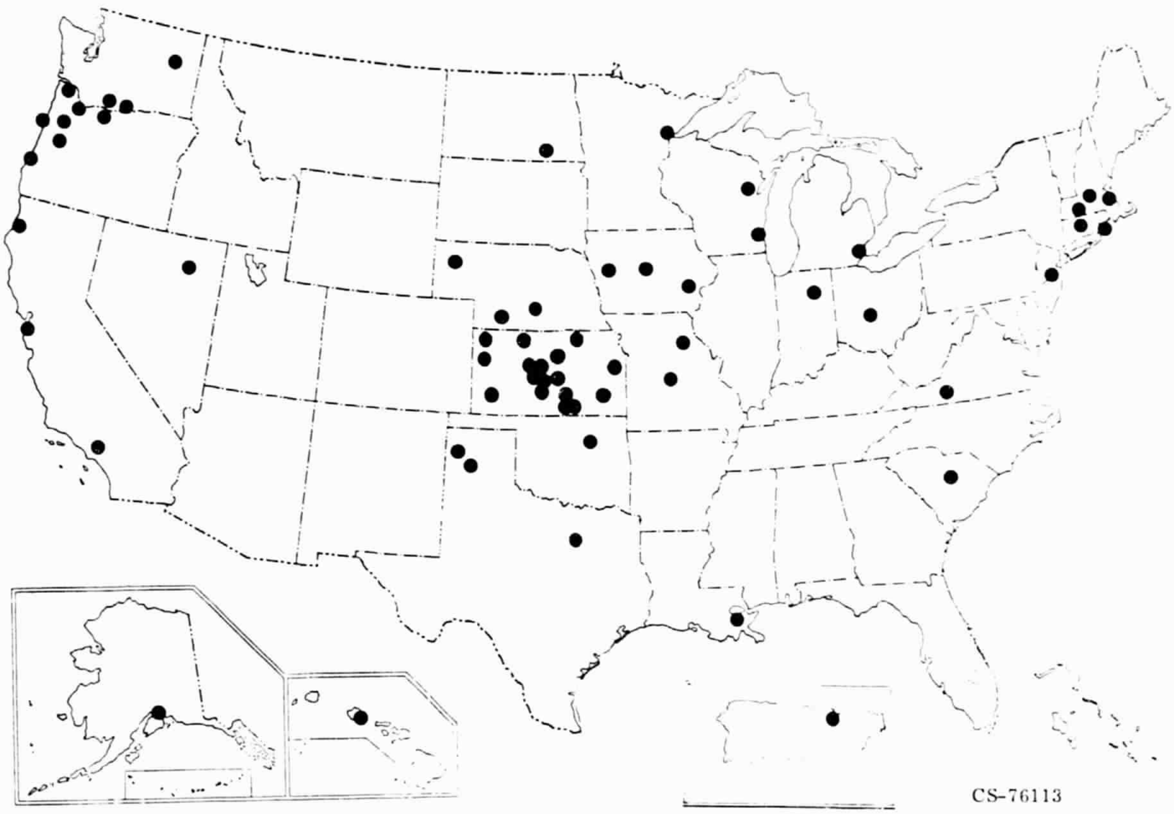



Figure 20. - Locations of utility companies that have expressed interest in the wind energy program.


Figure 21. - 60M (200 H) meteorological tower at Plum Brook wind turbine site.

| | 76 | 77 | 78 |
|---|---|---|---|
| SELECT SITES FOR MET. TOWERS | ▽ | | |
| SELECT MOD-0A SITES | ▽ ▽ | | |
| SELECT MOD-1 SITES | | ▽ | ▽ |

Figure 22. - Schedule for selecting mod-0A and mod-1 wind turbine sites.